Two Low Frequency Surveys of Radio Galaxies

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Abstract

High resolution, low frequency observations are very efficient for surveying radio galaxies because of: 1) the wide field of view and 2) the bias toward steep spectrum (lobe dominated) emission. Here I present preliminary results from two ongoing low frequency radio surveys: the 4 Meter All Sky Survey (4MASS) and the low frequency counterpart to the XMM-Large Scale Structure (XMM-LSS) survey. 4MASS is an NRL-NRAO project to survey the entire sky above $\delta = -20°$ at 74 MHz with a resolution of $1.3'$. So far, 0.66 steradians have been observed and over 5000 objects identified, with the steep spectrum objects being followed up in a search for high redshift radio galaxies. The XMM-Large Scale Structure (XMM-LSS) survey is a major project underway to map the large scale structure of the universe out to cosmological distances. We are conducting a survey at both 325 MHz and 74 MHz in the 8×8 square degree XMM-LSS region. The radio counterpart to this deep X-ray survey is designed to explore the relation of the large scale structure to the location and properties of extragalactic radio sources. Statistical results of preliminary analysis of these two surveys are presented.

Key words: radio galaxies, surveys, low frequency radio

Table 1
A-configuration Observation Results

Frequency	Resolution	RMS Noise	Survey Area	Source Detections
325 MHz	$6.3''$	0.8 mJy/b	5.6 $\deg^2$	256
74 MHz	$30''$	55 mJy/b	110 $\deg^2$	211

1 Radio Counterpart to the XMM-Large-Scale-Structure Survey

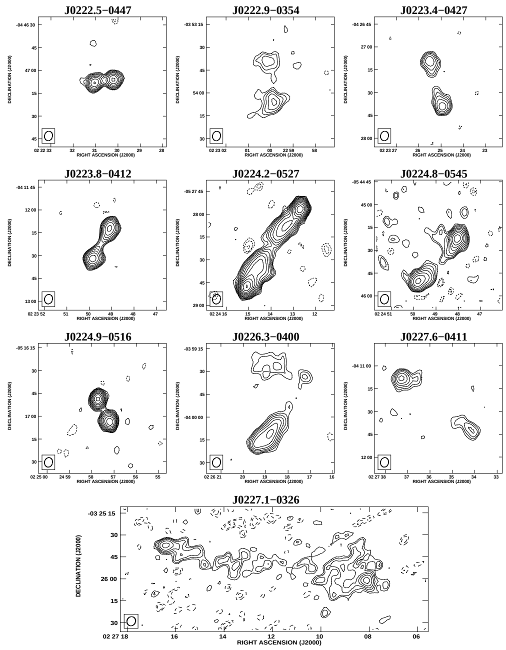
The XMM Large Scale Structure Survey (XMM-LSS) is a deep X-ray survey designed to map the distribution of groups and clusters of galaxies out to a redshift of $z = 1$ (Pierre et al., 2001). The planned X-ray identification of cluster candidates combined with spectroscopic follow-up will provide an unprecedented view of the large scale structure of the universe. With the prospect of these data, we conducted a low-frequency VLA survey of the XMM-LSS region in order to investigate the relationship between the population of cosmological radio sources and large scale structure.

Preliminary A-configuration observations have been taken. The observation parameters for both 74 and 325 MHz are summarized in Table 1. While most sources were unresolved, or only slightly resolved, there were several extended sources imaged in each frequency. Samples of some of the largest sources are shown in Figures 1 and 2. For a comprehensive description of these observations, see Cohen et al. (2003a). The main scientific results from these low frequency surveys will come from comparison to the X-ray and optical data in this field. The XMM observations have begun, and several candidate clusters have been identified. Preliminary comparisons should come soon.

2 4MASS: The 4 Meter All Sky Survey

2.1 Introduction

The new 74 MHz system on the Very Large Array, fully implemented in 1998 (Kassim, Perley, Erickson, & Dwarakanath, 1993), has opened up a new window into the previously unexplored regime of very low frequency radio observations at high sensitivity and sub-arcminute resolution. Already, this system has been used to explore a variety of subjects including the ISM, supernova remnants, the galactic center environment, cool gas in normal galaxies, galaxy



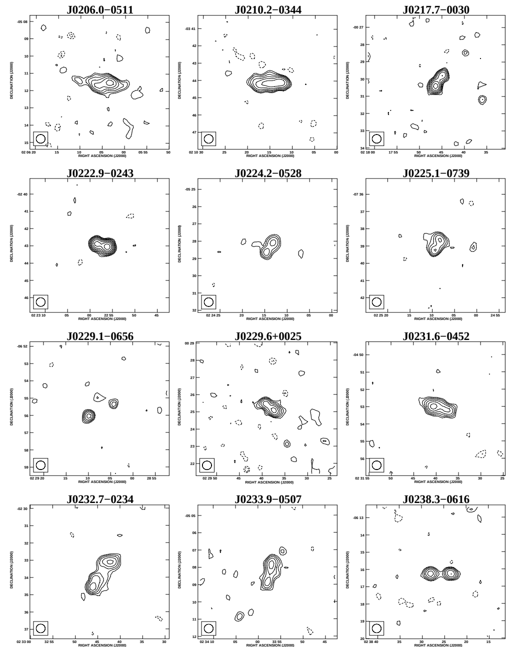


Fig. 1. Left: A sample of some of the larger resolved sources from the XMM-LSS radio counterpart observations at 325 MHz. The angular scale is the same in each image. Contour levels are at 2.5 mJy/beam × (-2, -1.4, -1, 1, 1.4, 2, 2.8, 4, 5.8, 8, ...) for each image.

Fig. 2. Right: A sample of some of the resolved sources from the XMM-LSS radio counterpart observations at 74 MHz. The angular scale is the same in each image. Contour levels are at 150 mJy/beam × (-2, -1.4, -1, 1, 1.4, 2, 2.8, 4, 5.8, 8, ...).

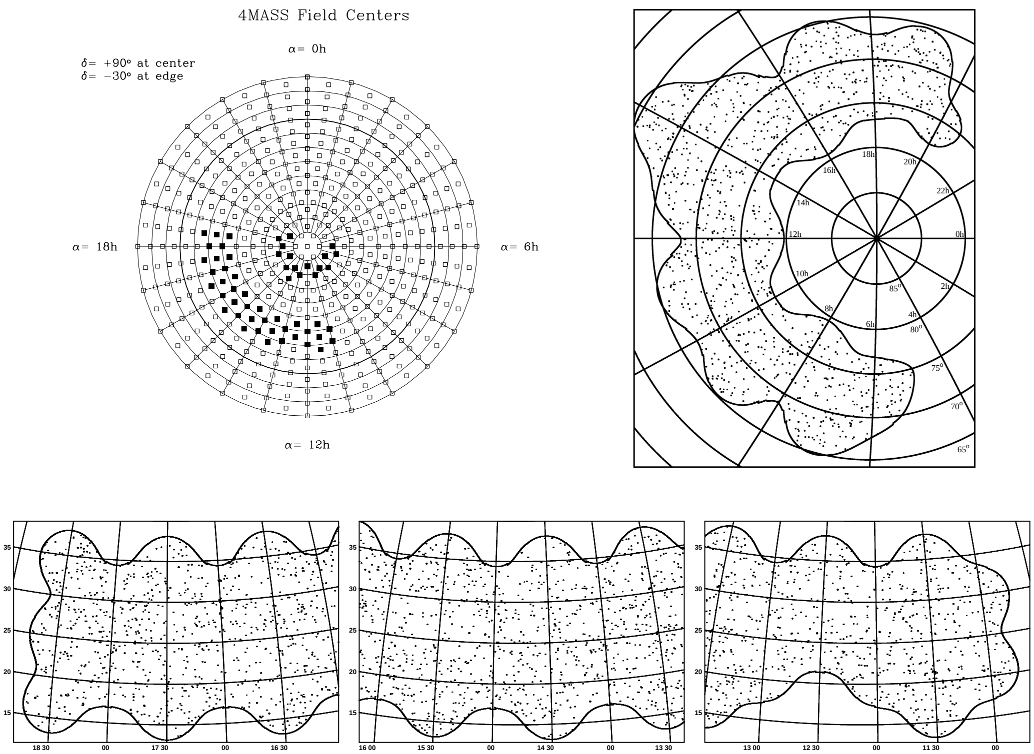
clusters, large scale structure and high redshift radio galaxies. In order to further explore the scientific potential of this new frequency-resolution regime, a 4 Meter All Sky Survey (4MASS) is in progress. The goal of this survey is to map the entire sky north of $\delta \geq -30°$, to a resolution of $80''$ with a 5σ source detection limit of 0.5 Jy/beam.

2.2 Preliminary Data

The 4MASS observations are taken with the B-configuration VLA with 1.5 MHz bandwidth centered on 73.8 MHz, with 2 polarizations and 6.67s integrations. We designed a roughly hexagonal grid of pointing centers, with a separation of $\Delta \approx 0.72 \times \theta_p \approx 8.6°$, where $\theta_p \approx 11.9°$ is the FWHM primary beamwidth.

Currently, we have observed 54 fields in two regions of the sky. Figure 3 shows the pointing grid as well as maps of the regions of sky covered so far. We have now surveyed a total area of 0.9 steradians which represents nearly 10% of the full survey. We have detected 6,406 sources at the 5σ level. For a full

4MASS: Status of Observations



• = source with peak flux density> 1 Jy/beam

Fig. 3. Current status of 4MASS observations. In the maps, each point represents a source with a peak flux density of at least 1 Jy/beam.

description of these preliminary observations see Cohen et al. (2003b)

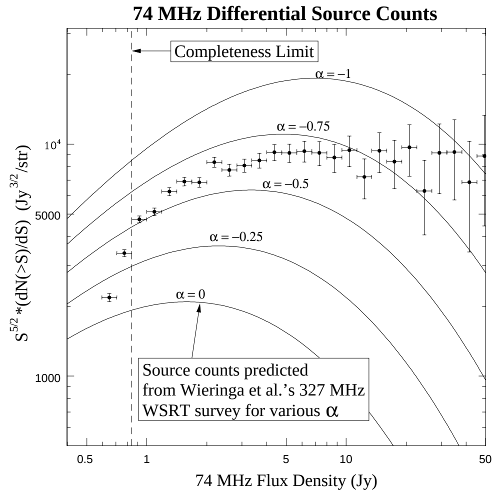
2.3 Preliminary Analysis

2.3.1 Source Counts

With so many sources, it is possible to determine meaningful statistics on the properties of sources at 74 MHz. Figure 4 shows the differential source counts. It is clear from comparison to a deep WSRT survey (Wieringa, 1991) that the difference between 74 MHz and 327 MHz source counts is more complicated than a simple spectral index adjustment.

2.3.2 Spectral Measurements

We measure the spectral index of each 4MASS source by comparing to the flux density in the 1.4 GHz NVSS catalog (Condon et al., 1998). Every 4MASS source had a NVSS counterpart with 45″, and the median spectral index was $\alpha = -0.8$.



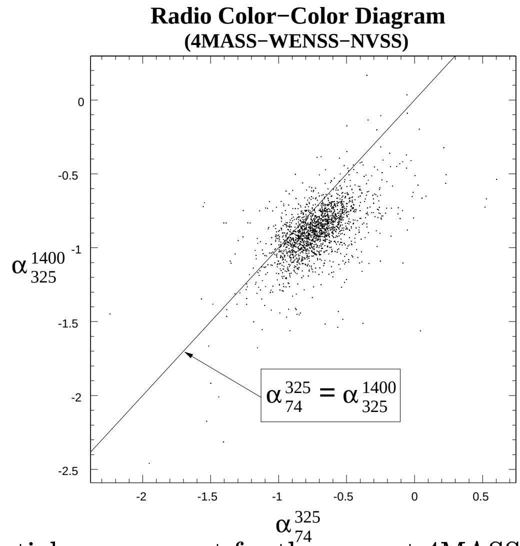


Fig. 4. (Left) Euclidean normalized differential source count for the current 4MASS data. The solid lines represent the source counts from a deep WSRT 327 MHz survey (Wieringa, 1991) projected to 74 MHz according to various assumed spectral indices.

Fig. 5. (Right) Radio color-color diagram for the polar region sources. Flux measurements at 74, 325 and 1400 MHz were taken from the 4MASS, WENSS and NVSS catalogs respectively. Note that most sources have a spectrum that flattens in the lower frequency interval. The median spectral index change for these sources was: $Med(\alpha_{74}^{325} - \alpha_{325}^{1400}) = 0.16$.

For those sources with counterparts in both the NVSS and the 325 MHz WENSS catalog (Rengelink et al., 1997), we plot a radio color-color diagram of α_{325}^{1400} versus α_{74}^{325} (Figure 5). First we note a clear positive correlation between the spectral indices in these two frequency intervals. We also find that most sources have $\alpha_{325}^{1400} < \alpha_{74}^{325}$, with a median difference of 0.16. To raise α_{74}^{325} by 0.16, requires a lowering of S_{74MHz} by 27%, which is much higher than the flux density error for the average source, and also much higher than the 74 MHz flux scale error estimate of 5% (Kassim et al., 2003). We therefore detect a significant flattening in the average spectrum of these sources.

2.3.3 USS Source Follow-up

One major scientific goal of this survey is to explore ultra-steep spectrum (USS) objects ($\alpha < -1.2$; $S \propto \nu^{-\alpha}$). Particularly, with the known tendency for high redshift radio galaxies to have steep spectrum, USS objects are of great interest. As USS sources are rare, 4MASS, with its large survey area, is ideal for identifying large numbers of such sources.

In the 0.9 steradians surveyed so far, we have identified 137 sources with spectra steeper than $\alpha < -1.2$. We have begun a follow-up campaign on these USS sources, by first obtaining deep, high resolution 1.4 GHz observations in the VLA A-configuration in order to determine the morphologies of these sources and to better determine their positions for later optical follow-up. Roughly half the sources we have followed-up, show compact, FR II morphologies. The fact that such sources are ultra-steep spectrum objects down to a frequency as low as 74 MHz is highly suggestive of a high redshift radio galaxy. Optical follow-up of these sources is planned.

2.4 Future Plans for 4MASS

The final proposal for the remaining VLA time needed to complete 4MASS was submitted on October 1, 2002. The next B-configuration occurs from September through December of 2003. The data reduction timescale (well known, as we now have much experience with the pipeline data reduction routines) is 3 to 4 months. This project is being conducted as a service to the astronomical community. As soon as the data is reduced and verified it is posted to the 4MASS web site:

<URL: http://lofar.nrl.navy.mil/4MASS>.

References

Cohen, A. S., Röettgering, H. J. A., Kassim, N. E., Cotton, W. D., Perley, R. A., Wilman, R., Best, P., Pierre, M., Refregier, A., Birkinshaw, M., & Zanichelli, A. 2003, "Preliminary Results from the Low Frequency Radio Counterpart of the XMM Large Scale Structure Survey", (in prep)

Cohen, A. S., Lane, W. M., Lazio, T. J. W., Kassim, N. E., Perley, R. A., Cotton, W. D., Condon, J. 2003, "A Sub-Jansky, High-Resolution Survey of 0.9 sr at 74 MHz", (in prep)

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693

Enßlin, T. A., Biermann, P. L., Klein, U., & Kohle, S. 1998, A&A, 332, 395

Kassim, N. E., Perley, R. A., Erickson, W. C., & Dwarakanath, K. S. 1993, AJ, 106, 2218

Kassim, N. E., Lazio, T. J. W., Erickson, W. C., Perley, R. A., Cotton, W. D., Greisen, E. W, Hicks, B., Cohen, A. S., Lane, W. M., & Rickard, L. J. 2002,"The 74 MHz System on the Very Large Array", (in prep)

Pierre, M., Alloin, D., Altieri, B., Birkinshaw, M., Bremer, M., Böhringer, H., Hjorth, J., Jones, L., Le Fèvre, O., Maccagni, D., McBreen, B., Mellier, Y., Molinari, E., Quintana, H., Röttgering, H., Surdej, J., Vigroux, L., White, S., Lonsdale, C. 2001, The Messenger, 105, 32

Rengelink, R. B., Tang, Y., de Bruyn, A. G., Miley, G. K., Bremer, M. N., Roettgering, H. J. A., & Bremer, M. A. R. 1997, A&PS, 124, 259

Wieringa, M. H. 1991, Ph.D. Thesis, Leiden University